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# New insights into the Kawah Ijen hydrothermal system from geophysical data

CORENTIN CAUDRON<sup>1,2,3\*</sup>, GUILLAUME MAURI<sup>4,5</sup>, GLYN WILLIAMS-JONES<sup>5</sup>,  
THOMAS LECOCQ<sup>2</sup>, DEVY KAMIL SYAHBANA<sup>6</sup>, RAPHAEL DE PLAEN<sup>7</sup>,  
LOIC PEIFFER<sup>8</sup>, ALAIN BERNARD<sup>3</sup> & GINETTE SARACCO<sup>9</sup>

<sup>1</sup>*Earth Observatory of Singapore, Nanyang Technological University, 50 Nanyang Avenue,  
Block N2-01a-15, Singapore 639798*

<sup>2</sup>*Royal Observatory of Belgium, Seismology Section, 3 avenue Circulaire,  
1180 Uccle, Belgium*

<sup>3</sup>*Department of Earth and Environmental Sciences, Université Libre de Bruxelles, 50 Avenue  
9 Roosevelt, 1050 Brussels, Belgium*

<sup>4</sup>*Center for Hydrogeology and Geothermics, University of Neuchtel, Neuchtel, Switzerland*

<sup>5</sup>*Department of Earth Sciences, Simon Fraser University, 8888 University Drive, Burnaby,  
British Columbia, V5A 1S6, Canada*

<sup>6</sup>*Centre for Volcanology and Geological Hazard Mitigation, Geological Agency, Ministry  
of Energy and Mineral Resources, Jalan Diponegoro 57, Bandung 40122, Indonesia*

<sup>7</sup>*University of Luxembourg, Faculté des Sciences, de la Technologie et de la Communication,  
6 rue Richard Coudenhove-Kalergi, L-1359 Luxembourg*

<sup>8</sup>*Instituto de Energías Renovables, Universidad Nacional Autónoma de México, Privada  
Xochicalco s/n, Centro, 62580 Temixco, Morelos, Mexico*

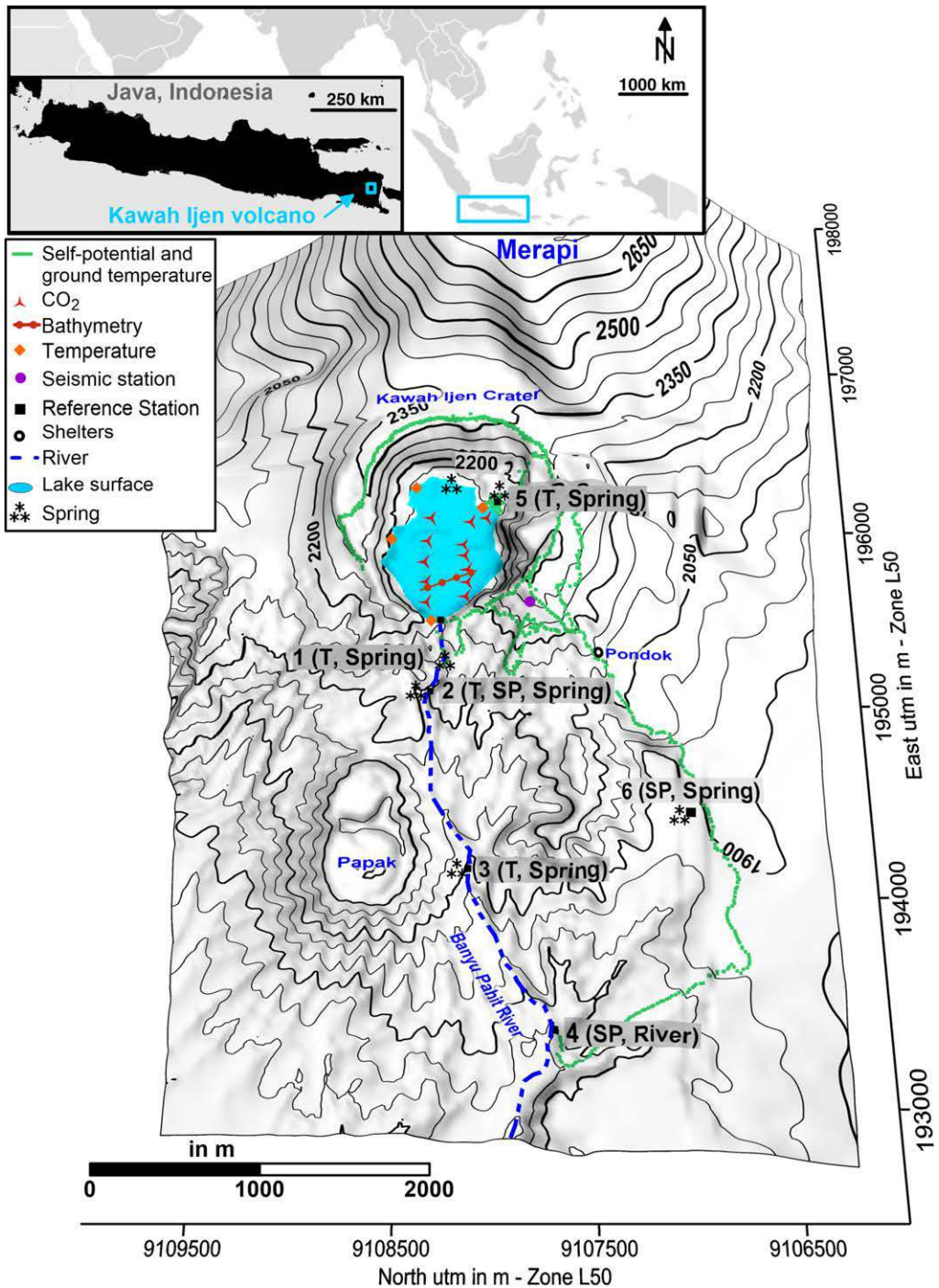
<sup>9</sup>*CNRS-UMR7330, Centre Europeen de Recherche et d'Enseignement en Geosciences de  
l'Environnement (CEREGE), Equipe Modelisation, Aix-Marseille Université (AMU),  
Europole de l'Arbois, BP 80, 13545 Aix-en-Provence cedex 4, France*

*\*Corresponding author (e-mail: corentin.caudron@gmail.com)*

**Abstract:** The magmatic–hydrothermal system of Kawah Ijen volcano is one of the most exotic on Earth, featuring the largest acidic lake on the planet, a hyper-acidic river and a passively degassing silicic dome. While previous studies have mostly described this unique system from a geo-chemical perspective, to date there has been no comprehensive geophysical investigation of the system. In our study, we surveyed the lake using a thermocouple, a thermal camera, an echo sounder and CO<sub>2</sub> sensors. Furthermore, we gained insights into the hydrogeological structures by combining self-potential surveys with ground and water temperatures. Our results show that the hydrothermal system is self-sealed within the upper edifice and releases pressurized gas only through the active crater. We also show that the extensive hydrological system is formed by not one but three aquifers: a south aquifer that seems to be completely isolated, a west aquifer that sustains the acidic upper springs, and an east aquifer that is the main source of fresh water for the lake. In contrast with previous research, we emphasize the heterogeneity of the acidic lake, illustrated by intense subaqueous degassing. These findings provide new insights into this unique, hazardous hydrothermal system, which may eventually improve the existing monitoring system.

Kawah Ijen volcano (Java Island, Indonesia) (Fig. 1) hosts a very active hydrothermal system that consists of the largest hyper-acidic lake on Earth (current volume *c.* 30 million m<sup>3</sup>, pH  $\sim$  0 and temperature  $>30^{\circ}\text{C}$ ), a hyper-acidic river that flows

down the western flank of the edifice, and an actively degassing high-temperature silicic dome ( $>200^{\circ}\text{C}$ ) (van Hinsberg *et al.* 2010). Hydrothermal activity within an active crater hosting a lake presents a significant hazard for the surrounding



**Fig. 1.** Map of Indonesia, showing the location of Kawah Ijen (East Java). The main panel shows the view from the west of Kawah Ijen volcano and its main features. Solid (green) line, Self-Potential (SP) profiles; three-pronged symbols, CO<sub>2</sub> measurements on the lake; black squares, reference stations; open circles, houses/shelters; dashed (cyan) line, Banyu Pahit river; shaded (blue) surface, lake; The dotted (red) line indicates the echo sounding profile used in Figure 4; diamonds, temperature sensor locations; three stars, springs. See online version for colours.

population and farming activities. Since the beginning of the twentieth century, a concrete dam on the west side of Kawah Ijen's crater has controlled the lake overflow that could flood the surrounding villages and fields (Caudron *et al.* 2015a). Further west, the acid river passes through many coffee plantations and other crops. Hydrothermal activity weakens the volcanic edifice over time (Opfergelt *et al.* 2006), increasing the risk posed by strong phreato-magmatic or magmatic explosions, as well as catastrophic release of the contaminated lake water that might be externally triggered (e.g. by an earthquake or lake drainage; Caudron *et al.* 2015a). Hence, a better knowledge of the hydrothermal system and its extent are required to improve forecasting of such catastrophic events. The hydrothermal system has thus been studied for more than a century, mostly by geochemists (Caron 1914; Hartmann 1917; van Bemmelen 1941; Mueller 1957; Delmelle & Bernard 1994, 2000; Takano *et al.* 2004; van Hinsberg *et al.* 2010, 2015; Palmer *et al.* 2011). Delmelle *et al.* (2000) developed the only existing volcano-hydrothermal model in which high-temperature magmatic gases are absorbed into shallow groundwater and produce a two-phase vapour–liquid hydrothermal reservoir beneath the crater. In this model, the condensing gases may have equilibrated in the liquid–vapour hydrothermal region at *c.* 350°C. The liquid phase of the hydrothermal reservoir consists of SO<sub>4</sub>–Cl waters that enter a convective cell through which the water circulates. The summit SO<sub>4</sub>–Cl reservoir flows laterally and mixes with meteoric-dominated water to produce the spring discharges of the hyper-acidic river. The model of Delmelle *et al.* (2000) is derived from the chemical and isotopic characteristics of the thermal water and fumarole discharges.

Geophysical studies have been conducted on volcanic lake surfaces and edifices to locate, discriminate and differentiate aquifers from each other (e.g. Finizola *et al.* 2002; Lewicki *et al.* 2003; Mauri *et al.* 2010), to image specific features at the lake surface (Ramírez *et al.* 2013) and to image sub-aqueous degassing features (Caudron *et al.* 2012). However, to the best of our knowledge these techniques have not been applied to the Kawah Ijen environment. Our geophysical investigations were conducted between July 2006 and August 2011. During this time, volcanic activity did not exceed the background values in seismic and volcanic lake parameters (Global Volcanism Program 2007, 2009; Caudron *et al.* 2015a) and hence, was considered as normal (alert 1 on a scale of 1–4). A swarm of distal volcano-tectonic earthquakes occurred on 21 May 2011 near the Kawah Ijen caldera, just prior to the last geophysical survey, and may have triggered the subsequent unrest that started in October 2011 (Caudron *et al.* 2015b).

## Instruments and methods

### *Temperature monitoring and survey*

The lake was initially surveyed for thermal anomalies using a type-K thermocouple suspended from a boat during the day and by thermal IR (Infrared, FLIR camera P25 PAL model) imaging from the crater rim at night. Based on the acquired information, a total of about 20 iButton temperature probes (accuracy of *c.* 0.5°C, resolution of *c.* 0.6°C) were placed at strategic locations to monitor the lake over the last five years (Caudron *et al.* 2015a, b). Four iButton probes were first embedded in a polyphenylene sulphide capsule with a silicone O-ring to protect the sensors from acidity. However, the protection proved inadequate and all four probes were lost. All other probes were therefore placed in sample bottles filled with neutral water. In addition, to avoid any acidic water infiltration, each bottle was wrapped with thick tape and weighted with an iron rod. A Teflon or nylon rope was wrapped around each bottle neck and protected by an additional layer of tape. The bottles were then suspended in the lake, while the rope was attached to a climbing piton stabilized near the lake edge. Depths of the bottles typically fluctuated between 1 and 5 m depending on the lake level at a given time.

Several iButtons were also installed in the Banyu Pahit River (<20 cm deep) at the upper spring sites (Palmer *et al.* 2011) (number 1, Fig. 1).

The crater rim ground temperature was surveyed every 20 m along the self-potential profiles with a K-type chrome-aluminum probe (accuracy of *c.* 0.2°C). In order to characterize any atmospheric influence, ground temperature was measured at >20 cm depth where possible. Atmospheric temperature was also measured at each survey point.

### *CO<sub>2</sub> and degassing surveys*

In 2007 and 2008, we attempted to record CO<sub>2</sub> concentrations every 20 m along the self-potential profiles (Fig. 1) with a CO<sub>2</sub> meter (a Vaisala GM70 with a GMP221 probe) with a concentration range up to 20% and an error of 0.02% CO<sub>2</sub> + 2% of the reading value. These attempts were unsuccessful because the fine ash surface layer was too compact for gas pumping and ash particles regularly blocked the gas probe filter.

In 2010 and 2011, a miniaturized NDIR CO<sub>2</sub> gas analyser (Bernard *et al.* 2013) suspended from a boat at a depth <30 cm recorded high concentrations of free CO<sub>2</sub> dissolved at shallow depths in the lake waters. The dissolved CO<sub>2</sub> concentrations were almost constant throughout the lake area.

In June 2010 and July 2011, degassing areas and lake bathymetry were also determined with a

single-beam dual frequency (50–200 kHz) Simrad echo sounder. When using a single-beam echo sounder in volcanic lake environments, the backscattering strength ( $S_v$ , in dB), corresponding to the concentrations of echoes in the water column, is the most reliable parameter (Caudron *et al.* 2012) and is calculated by:

$$S_v = 10 \times \log \left[ \left( \frac{I_s}{I_i} \right) \left( \frac{1}{v} \right) \right] \quad (1)$$

where the variables are defined as:  $v$ , pulse volume (in  $\text{m}^3$ );  $I_i$ , incident intensity (in dB);  $I_s$ , scattered intensity (in dB). The ratio  $[(I_s/I_i) (1/v)]$  is also termed the backscattering coefficient or  $sv$  (in  $\text{m}^{-1}$ ).

### Self-potential (SP)

To investigate the flow direction of groundwater and characterize the type of flow, the self-potential (SP) method was used (e.g. Corwin & Hoover 1979; Lénat 2007; Jouniaux *et al.* 2009; Mauri *et al.* 2012). A detailed description of the method can be found in the work of Lénat (2007), Jouniaux *et al.* (2009) and Aizawa *et al.* (2008).

The self-potential survey was carried out every year between 2006 and 2009 at the end of July and the beginning of August, i.e. during the dry season. Two SP profiles were surveyed every 20 m along the two main access routes. One profile was along the crater rim and the other to the south of the edifice (Fig. 1). In 2007, an additional south–north radial profile was created, going from the south crater peak, near the seismic station, to Pondok, where it branched to the north, ending at the Banyu Pahit River, and to the west, ending at Paltuding (Fig. 1). SP was measured with non-polarized copper/copper sulphate electrodes, whose polarity was checked at least twice a day. The measurements were recorded with a high-impedance multimeter (*c.* 200 Mohm). Each 20 m location was referenced with a handheld GPS and measurements were always taken in a shallow hole (from 5 to 20 cm deep) to ensure sufficient ground moisture. The resistivity contact of the electrode with the ground was always below 120 kohm, which gives a good level of confidence in the quality of the electrical potential (mV) measured in each hole. To determine whether the SP values reflected natural generation rather than poor contact between the electrode and moist ground, each record of the electrical potential was also complemented by a record of the contact resistance (kohm) between the electrode and the ground.

All self-potential profiles were closed in a loop or directly connected to a natural water source. Three different springs were used as 0 mV reference points: the Banyu Pahit spring (numbers 2, 4, Fig. 1),

the Inner crater spring (number 5, Fig. 1) and the Paltuding spring (number 6, Fig. 1). In 2007, the Banyu Pahit River, where it crosses the road, was also used as reference. The Kawah Ijen acid lake was not used as a reference due to significant signs of chemical heterogeneity at its surface and the likelihood of redox reactions and electrolysis phenomena in the water. Previous studies on the springs and river have shown that their chemical composition was relatively stable over the course of a day (van Hinsberg *et al.* 2010; Palmer *et al.* 2011). Hence, the springs and river were considered as good references, due to the constant water flow and their lower concentration in total dissolved elements in comparison to the lake (van Hinsberg *et al.* 2010; Palmer *et al.* 2011). Self-potential measurements were complemented by ground temperature surveys to detect any thermal anomalies.

### Multi-scale wavelet tomography (MWT)

MWT is a signal analysis method using several wavelets on the SP profiles to investigate depths of shallow groundwater systems. The wavelets are based on the dilation and covariance properties of the Poisson kernel, which is used to analyse potential field signals (i.e. electrical SP, gravity; magnetic) (Moreau *et al.* 1997, 1999; Martelet *et al.* 2001; Sailhac & Marquis 2001; Saracco *et al.* 2004, 2007).

These wavelets are the second and third vertical derivative (V2 and V3, respectively) and second and third horizontal derivative (H2 and H3, respectively). Each analysis was made with each wavelet over 500 dilations for a range of dilation from 1 to 20. In order to avoid artefacts, we only consider depths found to be significant by at least three of the four wavelet analyses.

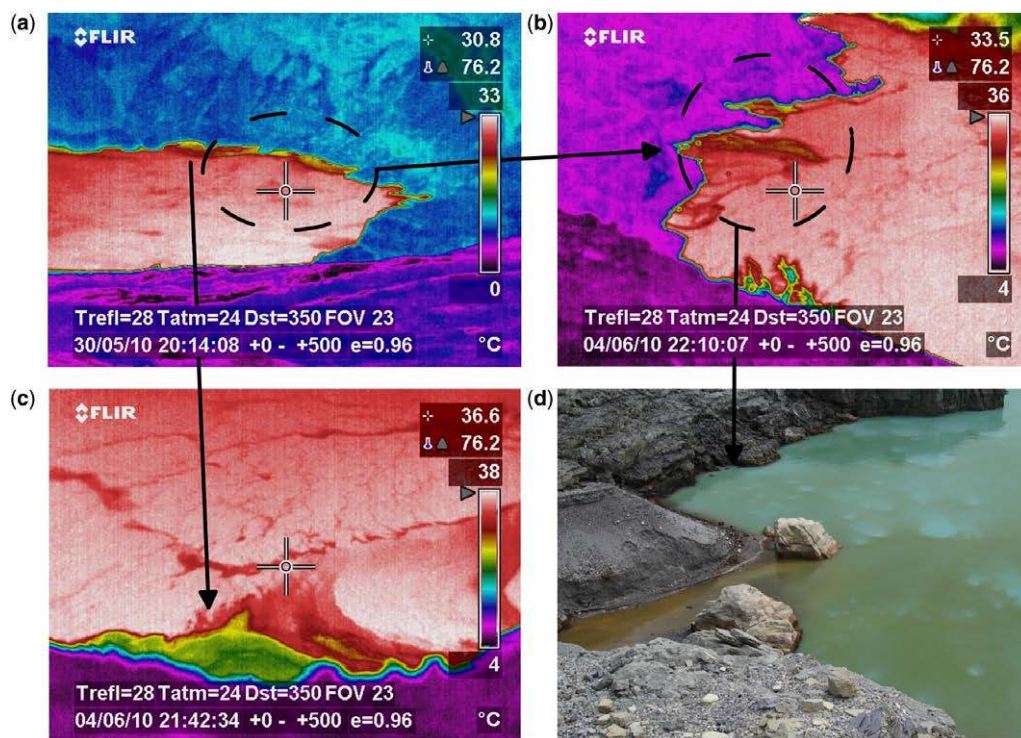
The main component of the electrical source is the electrokinetic effect, which is associated with the water flow displacement. Often, the strongest flow displacement is associated with the limit between the saturated and unsaturated zone (Mauri *et al.* 2010, 2012). Hence, this method helps investigate the depths of shallow groundwater systems. A complete description of the MWT method can be found in Mauri *et al.* (2011) with detailed examples found in Mauri *et al.* (2010, 2012).

## Results

### Lake temperature

The lake temperature is generally between *c.* 30°C and *c.* 45°C (Caudron *et al.* 2015a), but differs significantly in two areas. In the first area, in the NE part of the lake near the shore, the surface temperatures are 20°C lower (Figs 1 & 2a–c) due to cold water





**Fig. 2.** Thermal infrared images of the NE part of the lake (a–c) and the corresponding image in the visual spectrum (d). Colour bars in panels a, b and c display the temperature measured by the infrared camera. The brown precipitate on panel d marks an input of cold water.

flowing in from nearby Merapi volcano (a namesake of the well-known Mount Merapi in Central Java, Fig. 1). The colder temperatures are also manifested by discoloration (brown precipitate) (Fig. 2d) and a higher pH ( $\text{pH} \sim 3$ ) than elsewhere in the lake ( $\text{pH} \sim 0$ ). In the second area, close to the silicic dome (number 5 on Fig. 1), the lake temperatures are  $1\text{--}2^\circ\text{C}$  higher, probably due to numerous sub-aqueous fumaroles (see Lake degassing section).

Sudden temperature drops between October 2010 and January 2011 are related to heavy precipitation (Fig. 3a, b). When the sensor reaches a depth of *c.* 3 m below the lake surface, the rain no longer influences the lake temperature (i.e. after mid-January 2011, Fig. 3a, b). In contrast, temperatures measured at the surface by CVGHM observers are systematically biased during the rainy season. We also note the sudden increase in early May 2011 (Fig. 3b) that most likely reflects a local anomaly and/or inefficient mixing of lake waters.

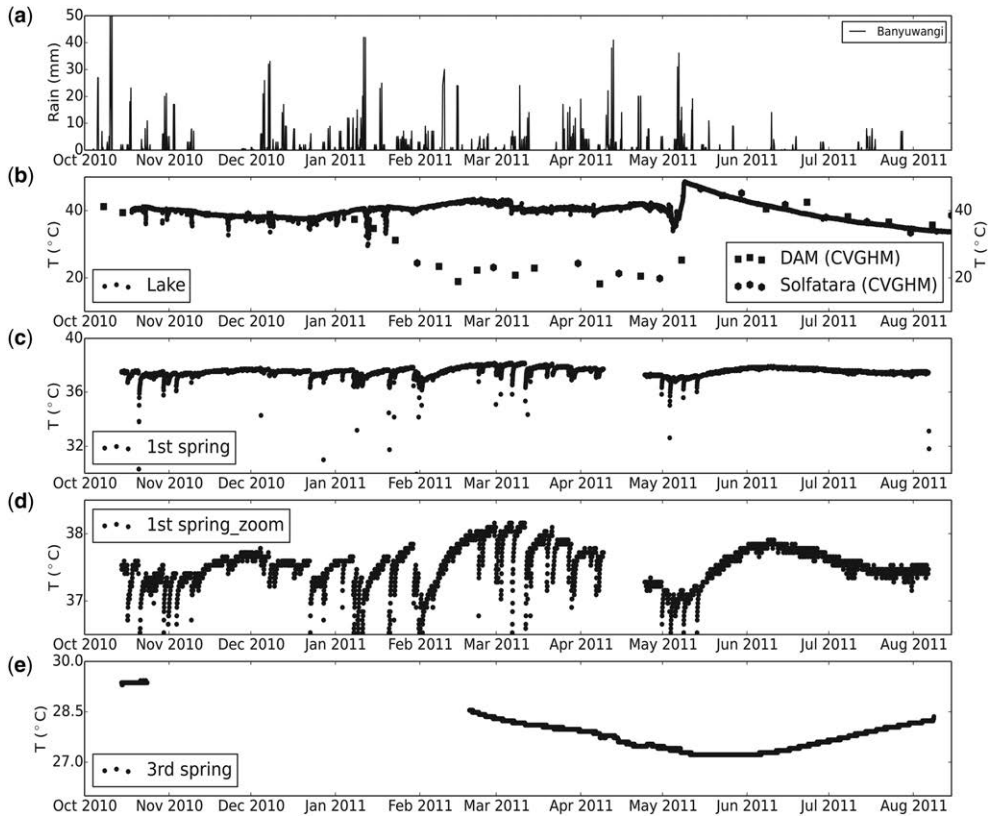
### *Temperatures of the Banyu Pahit springs*

The Banyu Pahit River is a confluence of three sets of springs (Delmelle & Bernard 2000; van Hinsberg

*et al.* 2010; Palmer *et al.* 2011). The first set of springs (number 1, Fig. 1), which lies just above a gypsum waterfall, near the dam, has temperatures of  $36.5\text{--}38^\circ\text{C}$  (Fig. 3c, d). Sudden temperature drops were recorded during periods of heavy precipitation (Fig. 3c, d). Long-term temperature variations still generally match those recorded in the lake (Fig. 3b–d), although these fluctuations are reduced by the thermal buffering effect of the rocks through which the water flows (Fig. 3b–d). Indeed, based on geochemical analyses, the first set of springs has been suggested to originate from the continuous seepage of lake waters through the rock basement (Delmelle *et al.* 2000).

The second set of springs (number 2, Fig. 1) has a very similar temperature pattern to the first one, and the sensor was consequently removed after a week-long measurement.

The third set of springs, located *c.* 1 km further to the west of the first set (number 3, Fig. 1), displays a clear seasonal temperature variation (Fig. 3e), with a decrease during the rainy season (November to May) and an increase during the dry season (Fig. 3e). In contrast to the first set of springs and the lake (Fig. 3b–d), temperature measurements



**Fig. 3.** Results from the continuous monitoring of (a) rainfall (mm) measured at Banyuwangi airport; (b) lake temperature (°C) measured weekly by CVGHM staff at the dam (isolated black squares) and next to the silicic dome (isolated black circles) and measured hourly by iButton sensors at the dam (linked black circles); (c) temperature measured in the first set of springs of Banyu Pahit (°C) (number 1 in Fig. 1); (d) temperature measured in the first spring of Banyu Pahit (°C) (zoom); (e) temperature measured in the 3rd set of springs of Banyu Pahit (number 3 in Fig. 1) (°C).

are not directly influenced by short periods of heavy precipitation, as the sensor is located in a cave and is therefore protected.

#### *Ground temperature along the crater rim and in the crater*

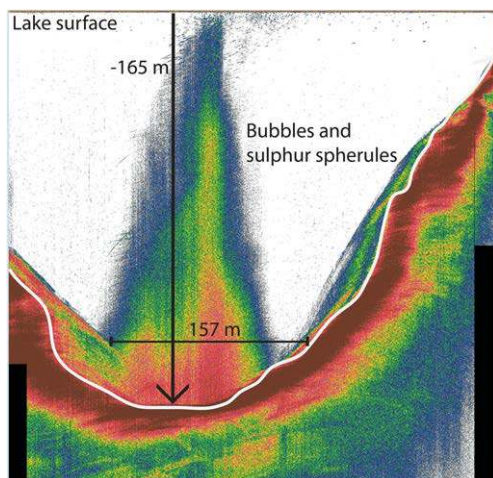
Ground temperatures were surveyed three times between 2006 and 2008. Along the crater rim no thermal anomaly was detected (background temperature of  $c. 20^{\circ}\text{C}$ ). In the crater, only thermal anomalies with very strong gradients ( $>150^{\circ}\text{C m}^{-1}$ ) were detected on the actively degassing silicic dome.

#### *Lake degassing*

Comparison between echo sounding surveys performed in 1996 by Takano *et al.* (2004) and in 2010–11 (this study) show little difference (Fig. 5a, b) aside from a decrease in lake level

attributed to filling by landslides and/or enhanced precipitation at the lake bottom (Caudron *et al.* 2015a). Importantly, numerous sub-lacustrine fumaroles were detected during our echo sounding survey (Figs 4 & 5c). The most impressive degassing plumes are observed in the centre of the lake (Fig. 4) but, based on visual observations, do not reach the lake surface. These areas show high  $S_v$  values (Fig. 5c) corresponding to high concentrations of matter in the water column, in this case bubbles and sulphur spherules. Contrary to the Kelud volcanic lake (Caudron *et al.* 2012), the presence of sulphur in the water column prevents deriving gas flux data directly from  $S_v$  values. However, we also find that degassing occurs close to the active silicic dome where the bubbles reach the surface (SE, Fig. 5c).

We investigated the concentrations of  $\text{CO}_2$  within the lake as this gaseous species has proven very useful for monitoring volcanic lakes (Christenson *et al.* 2010; Caudron *et al.* 2012).



**Fig. 4.** Echogram of the lake (dotted (red) line on Fig. 1) and its main features: upwelling bubbles mixed with sulphur spherules (50 kHz channel). Dark red colours indicate high concentrations of echoes ( $S_v = -30$  dB;  $S_v$  is the volume backscattering strength), whereas light blue colours are low concentrations ( $S_v = -70$  dB). The white line is the lake bottom. See online version for colours.

The concentrations of gaseous  $\text{CO}_2$  measured at 12 different locations was all in the range of 5–14 vol%. Although no spatial anomalies were detected at the lake surface, the concentrations were higher in 2011 than 2010. This may be explained by the higher level of volcanic activity (Caudron *et al.* 2015b) or by a colder lake temperature compared to 2010 (Caudron *et al.* 2015b). Indeed,  $\text{CO}_2$  concentration reflects a steady-state balance between  $\text{CO}_2$  supplied to the lake by hot springs (in a dissolved form) and by direct degassing, and  $\text{CO}_2$  lost by diffusion at the air–water interface (Bernard *et al.* 2013).

### Self-potential along the crater rim

Between, 2006 and 2009, the self-potential (SP) results show only minor variation of the natural electrical potential around the crater and toward the SW (Fig. 6). Over the years, only two positive SP anomalies of very limited extent show a correlation with strong hydrothermal surface alteration (1 and 2 on Fig. 6). Therefore, these two small anomalies (less than 20 mV in amplitude, a few hundred m in width) are likely due to the strong surface alteration, rather than evidence of rising hydrothermal fluids. In addition, temperature measurements show no sign of anomalies in either of these locations.

The strongest SP decrease is located on the east and north rim of the crater (Fig. 6). On the west

side of the crater, increases in the SP values are associated with decreases in elevation towards the river spring (Fig. 6). On the south flank of Kawah Ijen and along the path to and on the main road, the SP variations are inversely associated with decreasing elevation, which is typical of gravitational down flow of water in a cold aquifer (Lénat 2007).

Around the crater rim, the analyses of the SP/elevation gradient show clear inverse gradients that typically characterize gravitational down flow (Fig. 7), except for section 4, which shows no gradient at all. Three distinct aquifers can be characterized, the West, the South and the East aquifer. The latter extends toward the north. Traditionally, as presented in the work of Lénat (2007), SP/elevation gradients are best used parallel to the flow direction. On a crater rim, as on Kawah Ijen, strong topography variations prevent these types of profiles. In our case, the SP profile (Fig. 7) is perpendicular to the flow direction, but does not change the interpretation of the inverse SP/elevation gradient as long as the gradient is clear. No gradient or a normal gradient is often considered to represent rising water flow (Lénat 2007); however, when the SP profile is perpendicular to the flow direction, as here, it would be hazardous to consider section 4 of the profile as a rising flow (Fig. 7). As there is no thermal anomaly, and because the SP variations are around 20 mV, it is more likely that the SP variations in section 4 (Fig. 7) are due to internal variation in the aquifer surface geometry.

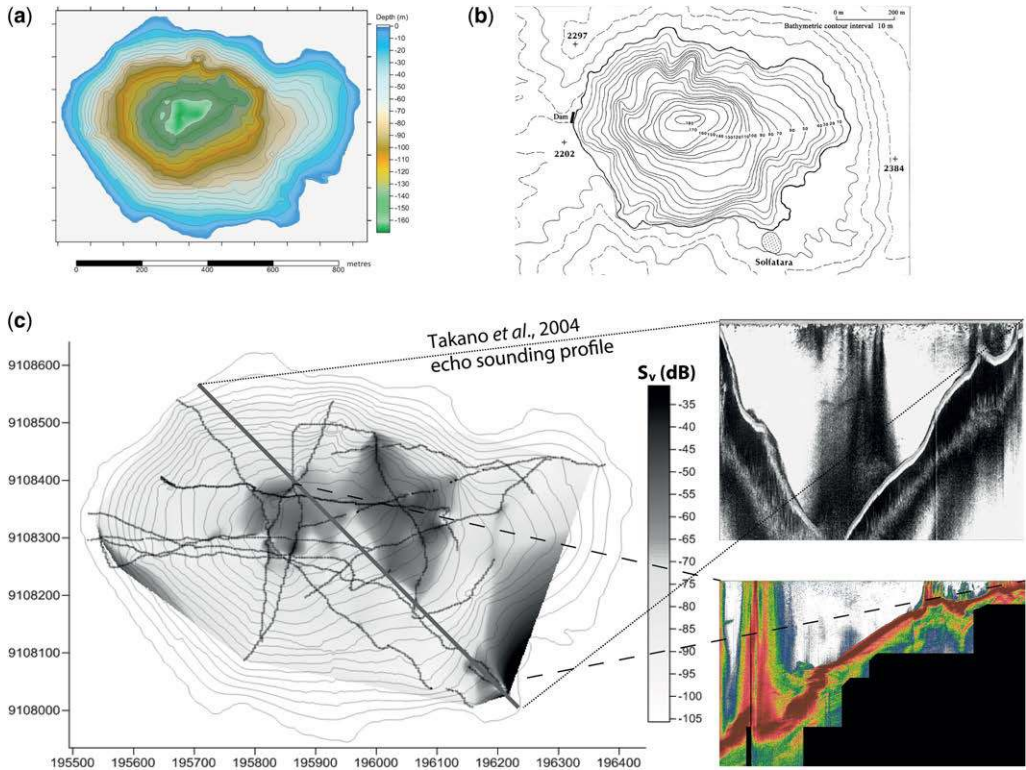
MWT was used to estimate the depth of the main sources of electric potential. On average, the aquifers are around 100 m deep (Table 1). Results of the MWT from SP data consist of 189 depth values measured with four different wavelets between 2006 and 2009 (Table 1). On the basis of their position along the SP profiles, the depth values were grouped into 26 depths (8 in 2006, 9 in both 2007, 2008 and 11 in 2009). Using only depths found with at least three wavelets that are spatially well located over the four years (along the profile), we characterize six datasets along the crater rim, which are named for their relative position from the crater: North, NE, East, SE, South and SW (Fig. 8). No obvious change in depth occurs from 2006 to 2009, within the uncertainty of the MWT analyses (Fig. 8a–f).

## Discussion

### Geophysical methods in hyper-acidic environments

Acidity of the water is an important factor to consider when investigating both surface and ground-water bodies on an active volcano, because (1) it





**Fig. 5.** (a) Kawah Ijen bathymetry is displayed using contour lines (10 m intervals). (b) Kawah Ijen bathymetry carried out in August 1996 (from Takano *et al.* 2004) (c)  $S_v$  (mean volume backscattering strength) map. Black dots represent the echo sounding profiles carried out during two campaigns in 2010 and 2011. Two insets show echograms acquired by Takano *et al.* (2004) in 1996 (black and white, upper right) and in 2010 (lower right). Dotted and dashed lines correspond to the 1996 and 2010 profile locations, respectively.

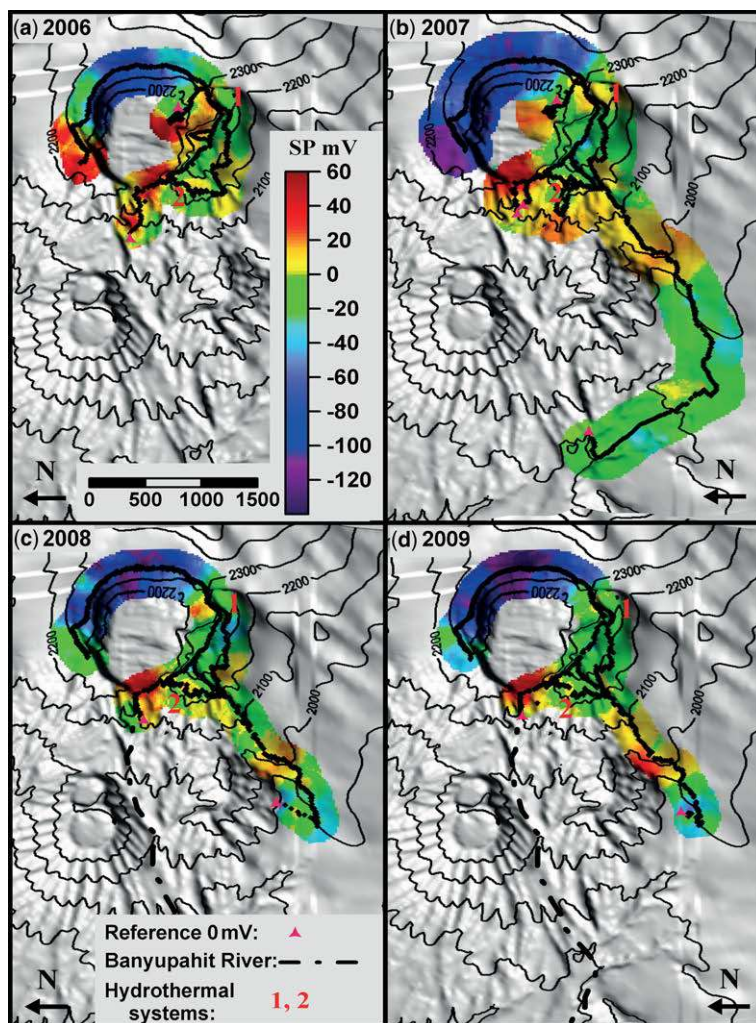
may affect the physical properties that are measured; and (2) it will attack and corrode equipment.

Previous work on acidity showed that it may have a significant impact on electrical generation. Indeed, studies have shown that pH is the expression of the balance in ions within the water fluid, which will affect the electrical generation (Guichet & Zuddas 2003; Hase *et al.* 2003; Aizawa *et al.* 2008). In some cases, such as when the pH is *c.* 3, it appears that the Zeta potential becomes null and electrical generation stops. However, it is still not clear what happens when the pH is *c.* 0. At Kawah Ijen volcano, the pH of the water flow (aquifer and hydrothermal system) approaches 0 and could be of significant importance for electrical generation. The spring waters range from pH 1–6 (Delmelle & Bernard 2000; Palmer *et al.* 2011). Our study shows that SP generation is well established over time (Fig. 7), but the amplitude of the anomalies are much lower than on other volcanoes (e.g. Lénat 2007; Aizawa *et al.* 2008; Mauri *et al.* 2012). Thus, in this study while the low pH may affect

the electrical generation, it does not appear to stop it. Further investigation of Zeta potential is needed to understand the true effect of hyper-acidic fluids on electrical generation.

Spring and lake temperatures are difficult to probe at Kawah Ijen. For *in situ* monitoring of the acidic lake waters, a protection similar to that described above (see Instruments and methodologies section) seems mandatory. Those probes not directly protected from the acidity were damaged within a month or less. Thermal infrared cameras allowed us to detect clear thermal anomalies at a safe distance. They would be also very useful for capturing convective cells and/or small explosions at the surface, such as in the Rincon de la Vieja and Poás volcanoes (Costa Rica). However, those instruments are also damaged by the corrosive gases emitted in the crater (Ramírez *et al.* 2013), hence, they need to be carefully protected.

Echo sounding techniques proved to be particularly effective for investigating degassing processes and dynamics in volcanic lakes (Caudron *et al.*



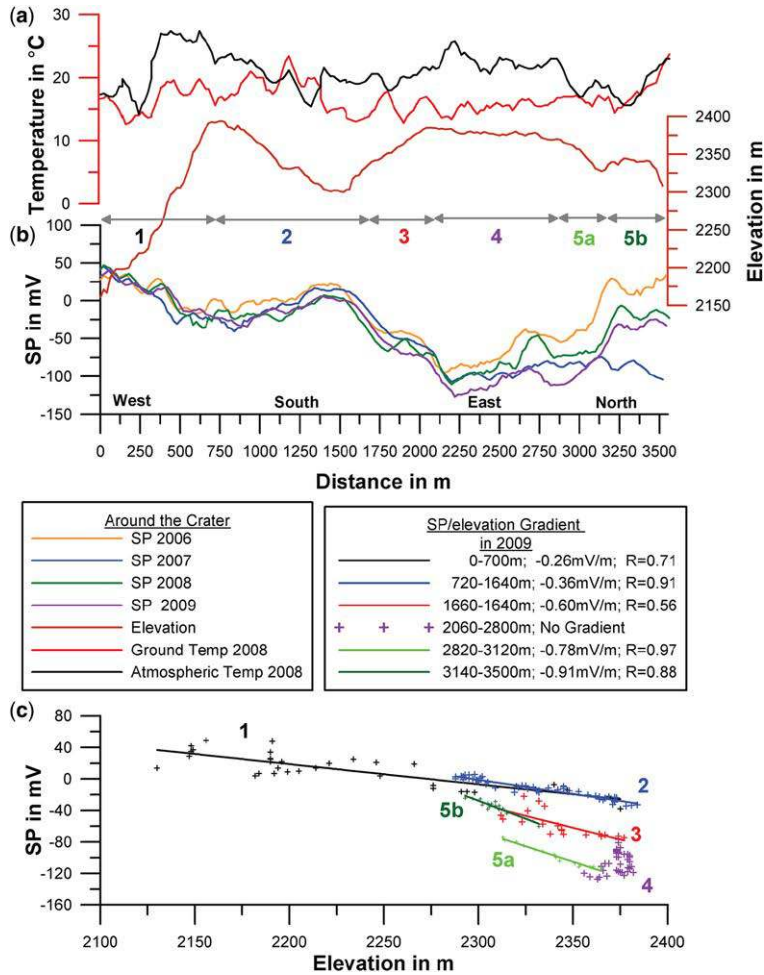
**Fig. 6.** Self-potential maps from 2006 to 2009. Distance and elevation contours, in m. All the data are referenced to the spring and river, (triangles). Dashed black line is the Banyu Pahit River. Black dots are the SP profiles. 1 and 2 represent hydrothermal areas.

2012), even in extreme conditions such as the Kawah Ijen environment. However, the presence of sulphur in the lake waters prevents a straightforward estimation of the  $\text{CO}_2$  flux, as for Kelud volcano (Caudron *et al.* 2012). A new approach based on the impedance contrast might be useful to tackle this problem and estimate the  $\text{CO}_2$  flux using echo sounding methods.

#### *Lake and hydrothermal system structure and dynamics*

A good understanding of the lake and hydrothermal structure is essential to correctly interpret the

variations in volcanic activity and to improve risk mitigation. In contrast to its geochemistry (Takano *et al.* 2004), the lake degassing and thermal features are not homogeneous, with clear anomalies controlled by the different aquifers in specific areas. In the centre of the lake, the absence of a thermal anomaly at the surface was unexpected considering the substantial degassing evidenced by the echo sounding surveys (Figs 4 & 5). Thermal anomalies were only observed at the surface close to the lake shores on the eastern side. Although they could not be echo sounded due to shallow depths, many areas of small bubbles are observed in those locations, as is the case at other lakes (e.g. Kelud,



**Fig. 7.** (a) Ground temperature; (b) SP profiles; (c) SP/elevation gradient of the crater rim. The numbers (1–5) represent the section of different SP/elevation gradients.

Central Java, Indonesia; Caudron *et al.* 2012). A weakened hydrostatic pressure might explain the preferential gas release close to the shores. Hence, the lake morphology is a critical factor in correctly assessing the degassing and thermal processes acting in volcanic lakes.

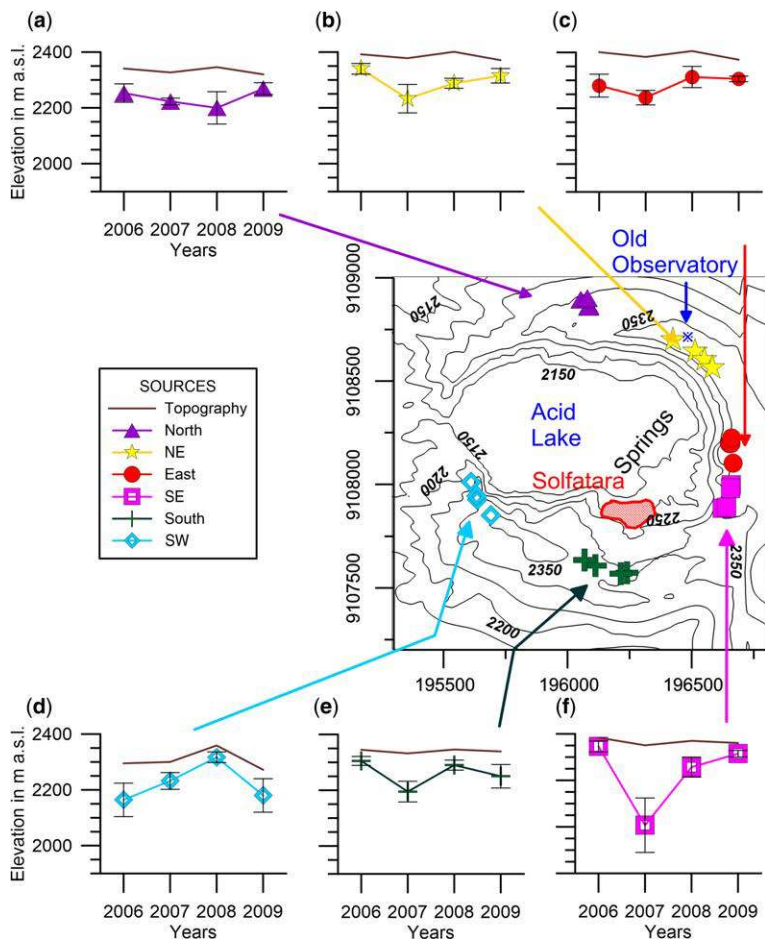
The four years of SP and ground temperature measurements did not reveal any significant sign of shallow hydrothermal activity outside the crater. The main hydrothermal activity is thus most likely restricted to the active crater. The hydrogeological system consists of three aquifers.

The East aquifer flows from Merapi volcano (Fig. 1) down the slope and is discharged into the acidic lake (Fig. 6, solid (blue) arrows in Fig. 9). This is consistent with the persistent cold plumes imaged using the thermal infrared camera at

different periods of the year. This aquifer is most likely the main source of groundwater for the acidic lake.

The West aquifer is clearly visible on each SP profile and manifests at the surface through several acidic water springs (Fig. 6, dashed (green) arrow in Fig. 9).

The South aquifer flows from the south peak of the crater rim towards the south at least to the caldera floor (solid (blue) arrows in Fig. 9). Based on the electrical structure, the lack of anomalous ground temperature and the potable water spring located downstream, the South aquifer seems disconnected from the acidic lake and the crater hydrothermal system. Between Pondok and Paltuding (Fig. 9), the fresh water spring (number 6, Fig. 1) is likely one output of this aquifer based on the



**Fig. 8.** Water depth variation between 2006 and 2009. Depths are calculated by MWT based on SP profiles. Only depths obtained with 3–4 wavelets are presented here. Error bars reflect the scattering of the data.

topography and SP/elevation gradient that suggests water flow toward the spring (Fig. 6c).

An ephemeral North aquifer may be present inside the north rim of the crater, but the source of its water is not clear (Fig. 6). Information from a Dutch colonial topographic map reports the existence of an ephemeral aquifer (in Van Hinsberg 2000), which was believed to exist due to the presence of evaporite minerals and an observed spring; no spring has been observed recently. Based on the topographic surface and the SP/elevation gradient from 2006–8 on the north rim, the surface water flows from east to west at a similar or shallower depth than the north rim water table (Fig. 8a, for North aquifer, Fig. 8b, c, for East aquifer). Therefore, we may surmise that the North aquifer is only supplied with water coming from the East aquifer.

Such water flow is likely to occur only when the East aquifer level is very high.

Outside the crater area, the only hydrothermal expressions are of small extent and located SE and SW along the upper part of the south flank of the volcano (Fig. 6). Hydrothermal activity is not supported by ground temperature anomalies. On the SW flank, outcrops reveal no sign of hydrothermal alteration of the rocks. On the SE, numerous outcrops show a high level of hydrothermally altered rock. However, we could not determine whether these deposits are the remnant of former hydrothermal activity in this area or if they consist of remobilized deposits from a past eruption. The fact that the SE and SW hydrothermal expressions of zone 1 (Fig. 6) are of small extent and not associated to any ground temperature suggests that the



**Table 1.** *Water depths*

Profile name	Years	Number of wavelet	Distance x (m)	s x (m)	Depth (m)	s Z (m)	Elevation (m above sea-level)	UTM in m		
								East	North	Topography
North	2006	4	3118	20	-88	33	2253	196 088	9 108 861	2341
	2007	3	3136	10	-104	12	2223	196 086	9 108 857	2327
	2008	3	3236	17	-146	58	2200	196 055	9 108 892	2346
	2009	3	3192	13	-51	21	2269	196 081	9 108 898	2320
North-East	2006	4	2605	8	-52	19	2340	196 515	1 908 642	2392
	2007	4	2582	39	-145	51	2233	196 553	9 108 603	2378
	2008	3	2550	6	-113	18	2288	196 585	9 108 564	2401
	2009	4	2761	29	-56	26	2315	196 427	9 108 698	2384
East	2006	4	2103	25	-120	41	2281	196 654	9 108 200	2374
	2007	3	2144	26	-146	26	2238	196 660	9 108 200	2384
	2008	4	2161	7	-93	38	2312	196 663	9 108 227	2405
	2009	3	2064	6	-69	10	2305	196 669	9 108 106	2374
South-East	2006	3	1893	50	-38	24	2346	196 661	9 108 002	2384
	2007	3	1801	19	-344	117	2007	196 625	9 107 892	2351
	2008	4	1839	14	-113	43	2257	196 642	9 107 896	2370
	2009	3	1934	13	-45	14	2315	196 659	9 107 987	2361
South	2006	3	1233	54	-40	16	2305	196 241	9 107 583	2345
	2007	4	1234	40	-137	37	2195	196 216	9 107 577	2232
	2008	4	1144	14	-56	18	2290	196 114	9 107 616	2346
	2009	4	1106	5	-89	42	2250	196 070	9 107 643	2339
South-West	2006	4	390	10	-131	60	2164	195 612	9 108 015	2295
	2007	4	454	12	-68	30	2232	195 637	9 107 934	2300
	2008	4	608	5	-42	19	2317	195 692	9 107 858	2359
	2009	4	472	6	-92	60	2180	195 635	9 107 951	2272

Water depths calculated by multi-scale wavelet tomography (MWT) using the SP profiles acquired on the crater rim (s characterizes the scattering of the data). UTM, universal transverse mercator.

hydrothermal system was reduced due to a decrease of activity in this part of the volcano. Alternatively, the important formation of hydrothermal deposits (Scher *et al.* 2013; Berlo *et al.* 2014) may have self-sealed the hydrothermal fluid pathway somewhere between the surface on the SE flank and the crater hydrothermal system.

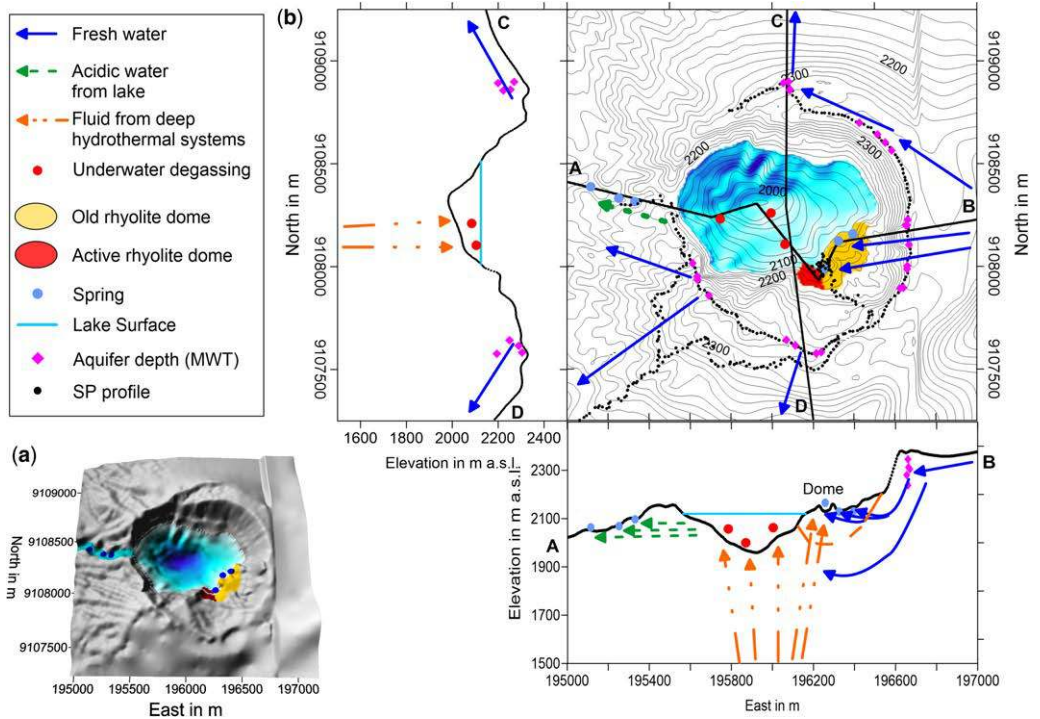
### *Perspectives for continuous monitoring*

In active craters, lakes are constituent parts of the hydrothermal system and, as such, record changes occurring at depth (Rowe *et al.* 1992; Ohba *et al.* 1994; Terada *et al.* 2011). Surrounding hydrogeology and lake volume are important factors that may buffer the changes occurring in the deeper parts of the hydrothermal systems. Changes in volcanic lake systems are essential to track as acidic lakes are considered to be constituent parts of a hydrothermal system. Therefore, precise observations and analyses of hot volcanic lakes may reveal even slight changes in the input of volcanic fluids originating from the underlying hydrothermal system (Terada *et al.* 2011).

Monitoring a spring related to the hydrothermal system allows for acquiring information safely,

especially during volcanic crises. Moreover, this may be particularly useful in Kawah Ijen where the important volume of the lake buffers the temperature fluctuations. However, the springs should not be too diluted by meteoric waters. According to Palmer (2011), the third set of springs (number 3, Fig. 1) may represent the deep hydrothermal system and could thus provide evidence for an increase in volcanic activity before any change in the volcanic lake. Our temperature data do not support the hypothesis of a deep hydrothermal source derived from the water geochemistry (Palmer *et al.* 2011), but rather indicate that the spring water is buffered by cold water input near the surface. Therefore, the third set of springs does not appear to be connected to the lake, but rather connected near the surface to meteoric waters coming from another valley unconnected to the crater of Kawah Ijen. Hence, our results suggest that this spring set is of limited benefit for future temperature monitoring. Closer to the crater, the first set of springs (number 2, Fig. 1) mostly derives from lake seepage. The strong buffering effect makes it less interesting from a monitoring perspective than the lake itself, currently monitored every hour by iButton sensors.





**Fig. 9.** Summary of the water flow structures on the Kawah Ijen volcano. (a) Digital elevation model (derived from SRTM (Shuttle Radar Topography Mission) data) merged with the 1:20 000 scale map from the topographical survey (1918; van Hinsberg *et al.* 2010), coordinates are in UTM; (b) 2D view and cross-sections (D–C: north and A–B: east). Solid (blue) arrows indicate fresh water flow, dashed (green) arrows acidic water flow from the lake, dotted (orange) arrows the fluid from deep hydrothermal systems, dark solid (red) circles the underwater degassing locations, pale shaded (yellow) areas the old silicic dome, darker shaded (red) areas the active silicic dome, pale solid (blue) circles the set of springs, pale (blue) line the lake surface, diamonds are aquifer depths (derived from MWT (multi-scale wavelet tomography)) and small black dots indicate SP profiles. See online version for colours.

Apart from the dam area, it would be useful to install a probe in the centre of the lake and another in the waters near the active silicic dome. The centre of the lake is less affected by streams of meteoric water flowing from the crater slopes. The fluids near the dome are less buffered than elsewhere due to a lower water level and interestingly, lie above a thermal and degassing anomaly. Hence, it would be useful to install a probe in these locations. From a technical point of view, equipping the centre of the lake is particularly difficult to achieve as it requires the use of a buoy.

While echo sounding may be very interesting for monitoring, it requires the use of a boat on the largest acidic lake in the world. Alternatives exist, however, such as the use of a remote-controlled boat. A single traverse every month that crosses the main degassing foci (Fig. 5) could be controlled safely from the lake shore. A hydrophone would be also very appropriate for Kawah Ijen. This instrument successfully detected hydroacoustic noise

precursors before the 1990 eruption in Kelud volcanic lake (Vandemeulebrouck *et al.* 2000), and was installed in a very similar lake environment (Ruapehu, New Zealand, Hurst & Vandemeulebrouck 1996).

Another parameter that would be very interesting to routinely monitor in Kawah Ijen is the  $\text{CO}_2$  concentration in the lake or above the lake surface. Previous work on  $\text{CO}_2$  monitoring gives useful information on the magmatic source and on the magmatic dynamics in Kawah Ijen (Vigouroux-Caillibot 2011; Scher *et al.* 2013). This gas is a relatively inert, pressure-transmitting medium in the hydrothermal environment (Christenson *et al.* 2010). In other volcanic lake systems, such as the Kelud system before the 2007 eruption, it was the earliest sign of an impending volcanic eruption (Caudron *et al.* 2012).

The use of geophysical instruments was very successful from a non-continuous perspective, but constitutes a significant challenge for continuous

monitoring in an environment such as Kawah Ijen. From the MWT results, the East, South and North aquifers are at about 100 m below the topographic surface. Along the crater rim, each of these aquifers is slightly above the lake level (Fig. 9). The uncertainty on the MWT results (mostly between 10 and 60 m) does not allow us to characterize any clear variation over time of the depth of the top of the aquifers. It should be noted that in 2007 (Fig. 8), 4 of the 6 inferred water table elevations showed a decrease of 30 m or more (depth name: NE, E, SE, S, Table 1). Along the crater rim, this decrease in the water table elevation correlates with the 2007 El Niño drought. This study cannot prove that there is a correlation, as there is no rainfall record for Kawah Ijen. However, it would be interesting in the future to investigate possible correlations between drought and depth of the aquifers and possible implications for the hydrothermal system of Kawah Ijen. As no shallow fluid is infiltrated in the SE and SW hydrothermal areas, a future increase of the electrical signature could indicate an infiltration from the deepest parts toward shallower areas. New infiltration from the self-sealed hydrothermal system within the upper part of the edifice could locally increase the pore pressure within the rock and, hence, generate rock fracturing that could contribute to destabilization of the volcanic edifice.

This study highlights the existence of a self-sealed hydrothermal system that has important implications for monitoring Kawah Ijen. Using modelling approaches coupled to observations, Christenson *et al.* (2010) concluded that the 2007 Ruapehu volcano (New Zealand) eruption was, at least initially, a gas-driven (effectively phreatic) event originating from an initially sealed hydrothermal system. Hydrothermal seals allow for development of pressurized, vapour-static gas columns beneath a vent (Christenson *et al.* 2010). Their failure led to decompression of the region beneath the seal, resulting in a downward-migrating pressure transient, and an upward expulsion of material in the rapidly expanding fluid phase. During the recent 2011–2012 (Caudron *et al.* 2015b) and 2013 unrest at Kawah Ijen, several seismic analyses and lake parameters (sudden seismic velocity drops, temperature increases preceded by drops, level increases, upwelling bubbles and increased gas emissions) indicated substantial build-up of pressure in the shallow system which could be attributed to an efficient sealing of the hydrothermal system followed by a sudden release of stored fluids.

## Conclusions

After more than a century of chemical investigations, the Kawah Ijen volcano has been surveyed

using geophysical methodologies providing new insights into one of the most exotic, but dangerous, magmatic–hydrothermal systems on Earth.

No significant hydrothermal activity is found outside the crater of Kawah Ijen volcano. Long-term and intense hydrothermal alteration, as well as possible preferential fracturing, seems to have allowed the intense shallow hydrothermal alteration system to completely seal itself within the upper volcanic edifice. This would leave the crater as the only path to release the volcanic fluids. Therefore, our results confirm past work on the geochemical signature of the hydrogeological fluids and volcanic gas (Palmer *et al.* 2011; Vigouroux *et al.* 2012; Scher *et al.* 2013; Berlo *et al.* 2014). While the southern aquifer is completely isolated from the lake and flows SE from the volcano, the eastern part of the lake receives a high amount of cold water flowing from nearby Merapi volcano. The North aquifer shows signs of fluctuations in its electrical potential signature, which are currently not fully constrained. The East, North and South aquifers appear to have their water table at an elevation that is above the lake level, but between 60 and 100 m below the crater rim. An acidic aquifer discharges on the west and feeds the Banyu Pahit River.

Thermal and gas anomalies are found in the SE part of the lake near the active silicic dome. Although the main conduit discharges an impressive amount of gas in the centre of the lake, no temperature anomaly was observed at the surface. Lake shores are the loci of bubbleings associated with upwelling of hot waters, probably due to a weaker hydrostatic pressure and less efficient convection. The lake morphology ultimately also dictates the degassing and thermal pattern.

The self-sealing also has strong implications for monitoring Kawah Ijen. Hydrothermal seals allow for development of pressurized, vapour-static gas columns beneath a vent (Christenson *et al.* 2010). Although it could only be suggested during the last sequence of unrest from 2011–13, several indicators suggests a substantial build-up of pressure in the shallow system followed by a sudden release of the stored fluids. We surmise that this process should be closely investigated in the future using modelling approaches coupled to available monitored parameters and observations.

Results and analyses from different geophysical surveys allow us to better understand how the hydrothermal system is structured. They also improve our knowledge of the lake dynamics and morphology, which is essential to correctly interpret the nature of the lake variations and better forecast catastrophic events.

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